

## CAN STELLAR MIXING EXPLAIN THE LACK OF TYPE IB SUPERNOVAE IN LONG-DURATION GRBS?

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## ABSTRACT

The discovery of supernovae associated with long-duration gamma ray burst observations is primary evidence that the progenitors of these outbursts are massive stars. One of the principle mysteries in understanding these progenitors has been the fact that all of these gamma-ray burst associated supernovae are type Ic supernovae, with no evidence of helium in the stellar atmosphere. Many studies have focused on whether or not this helium is simply hidden from spectral analyses. In this paper, we show results from recent stellar models using new convection algorithms based on our current understanding of stellar mixing. We demonstrate that enhanced convection may lead to severe depletion of stellar helium layers, suggesting that the helium is not observed simply because it is not in the star. We also present light-curves and spectra of these compact helium-depleted stars, compared to models with more conventional helium layers.

*Subject headings:* Supernovae: General, Stars: Neutron

## 1. INTRODUCTION

The association of supernovae occurring simultaneously with long-duration gamma-ray bursts (LGRBs) provides one of the strongest pieces of evidence behind a massive star progenitor for these bursts; see Woosley & Bloom (2006) and Hjorth & Bloom (2011) for reviews. To ensure that the jet is driven long enough to plow through the surrounding star, LGRB progenitors must not have extended hydrogen envelopes. Progenitors of LGRBs typically invoke either strong winds, or more likely, binary interactions, to remove the hydrogen envelope (Fryer et al. 1999; Woosley & Bloom 2006; Fryer et al. 2007). The standard engine behind LGRBs invokes the collapse of these progenitors down to a black hole, where the accretion onto the black hole drives the LGRB jet. These systems, typically arising from massive stars above  $20 M_{\odot}$ , have large helium shells. Without Wolf-Rayet mass-loss from the uncovered helium star, the helium mass for the Woosley et al. (2002) models predict helium masses in the  $1.0\text{--}25 M_{\odot}$  range for low-metallicity stars between  $15\text{--}100 M_{\odot}$  (the likely progenitor range for LGRBs and normal Ib/c supernovae).

Currently, all LGRB-associated supernovae and hypernovae are helium deficient, type Ic, supernovae (Woosley & Bloom 2006; Fryer et al. 2007; Sanders et al. 2012). Explaining the lack of Ib LGRB-associated supernova remains one of the primary problems with our current understanding of LGRB progenitors. A possible clue to this progenitor problem may be related to an equally puzzling problem in the ratio of normal type Ic to normal type Ib supernovae.

Smartt (2009) found that the number of Ic supernovae outnumbered the Ib supernovae. A more extensive, volume-limited, sample found that type Ic supernovae are twice as frequent as Ib supernovae (Smith et al. 2011).

One solution to these progenitor problems is to fine-tune the mass-loss from bare helium cores such that these stars lose their helium shells in a Wolf-Rayet phase while still retaining enough mass to collapse to a black hole. If true, there should be a strong metallicity dependence on the Ic/Ib rate. An alternate solution is to hide this helium. Hachinger et al. (2012) have calculated the maximum mass of helium that can be “hidden” in a type Ic supernova, placing limits between  $\sim 0.06\text{--}0.14 M_{\odot}$ . But Dessart et al. (2012) have argued that mixing in the supernova can alter the excitation level of the helium, effectively hiding it. Coupled with winds, this explosive mixing might be able to explain the high ratio of Ic to Ib supernovae. But, especially for the more massive progenitors expected in LGRBs, mixing in the supernova explosion is unlikely to explain the fact that all LGRB-associated supernovae lack helium lines.

We have discussed two possible solutions that seek to explain the lack of helium in supernova spectra: fine-tuned winds ejecting the helium prior to collapse and mixing in the supernova explosion making it difficult to observe the helium lines. We suggest a new, third solution. Prior to collapse, the star might efficiently burn the helium into heavier elements. Currently stellar structures are limited to the structure produced by mixing length theory, a recipe designed to mimic hydrodynamic mixing in stars. Using 3-dimensional hydrodynamics as a guide (Meakin & Arnett 2007), new algorithms are being developed to model stellar mixing (Young et al. 2005; Arnett et al. 2009). In this paper, we study massive star progenitors under these new mixing algorithms. We find that the latest improvements in the algorithm for mixing in stars burn much of the helium, leaving behind a helium shell mostly comprised of heavier elements and demonstrating the viability of this third solution. In section 2, we discuss this mixing and its effects on the helium shell layer. We conclude with light-curve calculations of these

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progenitors, demonstrating the extent to which these new models will change our picture of both LGRB progenitors and Ib/c supernovae in general.

## 2. STELLAR MIXING AND THE HELIUM SHELL

Most stellar models have relied upon modified variants of basic mixing length theory (Böhm-Vitense 1958) to include the complex physics of turbulent convection in the evolution of stars. But recent 3-dimensional models of this convection argue that the simple mixing theory is unable to capture the full physics behind turbulent convection (Meakin & Arnett 2007; Arnett et al. 2009, 2010; Arnett & Meakin 2011). These 3-dimensional studies have led to a revision of the theory behind turbulent convection in stars, focusing on both connections to the Kolmogorov (1962) theory of turbulent cascade (Arnett et al. 2009) and to the Lorenz (1962) strange attractor (Arnett & Meakin 2011).

The TYCHO code has been upgraded with an algorithm based on a physical analysis of 3D hydrodynamic simulations of convection, not an astronomically calibrated mixing-length theory. It includes non-locality and time dependence of flow, dynamical acceleration, turbulent dissipation, Kolmogorov heating, compositional effects and dynamically defined boundary conditions (instead of parameterized overshooting schemes), all in a single, self-consistent formulation. TYCHO also includes a 177 isotope nuclear network. The code is regularly tested against observations of double lined eclipsing binaries and cluster isochrones to ensure consistency and accuracy. It produces superior fits to observational test cases without adjustment of parameters (Young et al. 2005).

With this code, we have run 4 stellar model progenitors for type Ib/c supernovae with 4 different zero-age main sequence masses: 15, 21, 23, and 27  $M_{\odot}$ . These stars are modeled to collapse with final masses of 12.1, 12.8, 15.4, 16.7  $M_{\odot}$  respectively. In all cases, these stars retain some hydrogen at collapse and, without additional mass loss (e.g. from a binary common envelope phase or higher mass-loss rate), these stars will produce type II supernovae. Many GRB progenitors require binary interaction and we assume this interaction leads to the ejection of the hydrogen envelope. However, it is less likely that the common envelope will eject the helium envelope.

The abundance profiles (H, He, O, Si, S, Ar and heavy elements) for our 4 models are shown in figure 1. The 15  $M_{\odot}$  star retains a normal helium shell. But above 20  $M_{\odot}$ , mixing in the helium shell burns much of the helium into oxygen. This burning becomes more complete with increasing progenitor mass. By 27  $M_{\odot}$ , the helium fraction in the “helium” shell is below 15%. These abundances are vastly different from simulations (Woosley et al. 2002) using standard mixing length theory plus parameterized overshooting (Fig. 2). Mixing length theory produces, for a 23  $M_{\odot}$  star, a nearly 2  $M_{\odot}$  helium layer that is over 90% helium. With our new model, a 2  $M_{\odot}$  helium layer exists, but it is only  $\sim 20\%$  helium.

The mixing also changes the structure of the star. Figure 2 shows the differences in the entropy and density of our 23  $M_{\odot}$  and the Woosley et al. (2002) 23  $M_{\odot}$ . Our star has lower entropy in the helium layer, producing a

more compact star with densities nearly an order of magnitude higher in this region. The corresponding maximum stellar radius is over an order of magnitude lower.

## 3. SUPERNOVA OBSERVATIONS

To illustrate the role these different abundances have on supernova observations, we focus on the 23  $M_{\odot}$  progenitor, collapsing it with the same technique described in Young & Fryer (2007). The collapse code is a one-dimensional Lagrangian code developed by Herant et al. (1994). This code includes three-flavor neutrino transport using a flux-limited diffusion calculation and a coupled set of equations of state to model the wide range of densities in the collapse phase (see Herant et al. 1994; Fryer et al. 1999 for details). After the collapse, bounce, and formation of the proto-neutron star, we stop the code and remove the neutron star. We then artificially inject energy into the innermost zones to drive an explosion. For this model, we produced a  $5e51$  erg explosion. To study the effect of abundance differences on the light-curve and spectra, we run two models: one is our new 23  $M_{\odot}$  progenitor, the other is this same progenitor with the helium core abundances altered to match those from the Woosley et al. (2002) 23  $M_{\odot}$  progenitor (subsequently referred to as the Young and Woosley models, respectively). In this manner, we can focus only on the abundance differences and not on the structure differences we also discussed in section 2.

After the launch of the explosion, each model is mapped into RAGE (Radiation Adaptive Grid Eulerian), a Eulerian radiation-hydrodynamics code which includes adaptive mesh refinement (Gittings et al. 2008), where it is run out to several years. We post-process data from individual timesteps with the SPECTRUM code, which uses monochromatic opacities to calculate spectra and lightcurves. SPECTRUM allows us to study emission and absorption as a function of radius, as well as the effects of individual elements on observable spectra. This pipeline is described in detail in Frey et al. (2013).

To demonstrate the effects of the two different helium core abundances, we compare the resulting spectra, and lightcurves in several different bands. The compact nature of this progenitor produces a very short-duration burst, with the time from first peak in the v-band to its decay by over a magnitude lasting less than 10 days (Fig. 3). We are using identical stellar structures, so it is not surprising that the UV/optical lightcurves in figure 3 from the Young model are the same shape as the Woosley model. One obvious difference can be seen in the luminosities, as the Young model produces peak spectra at high energies (u band and higher) that are one magnitude dimmer than the Woosley model.

The differences are more striking in the spectra. Our SPECTRUM code calculates opacities by mixing opacities from individual elements, so we can artificially modify this algorithm to study the emission and absorption due to single elements by setting the opacity for a single element to zero. This allows us to compare spectra calculated without helium or oxygen to complete spectra and easily identify emission and absorption from those elements. As expected, the Young model shows much stronger effects from oxygen and weaker helium emission and absorption than the Woosley model. At 1e3s (Fig. 4, top), we see helium absorption in both models

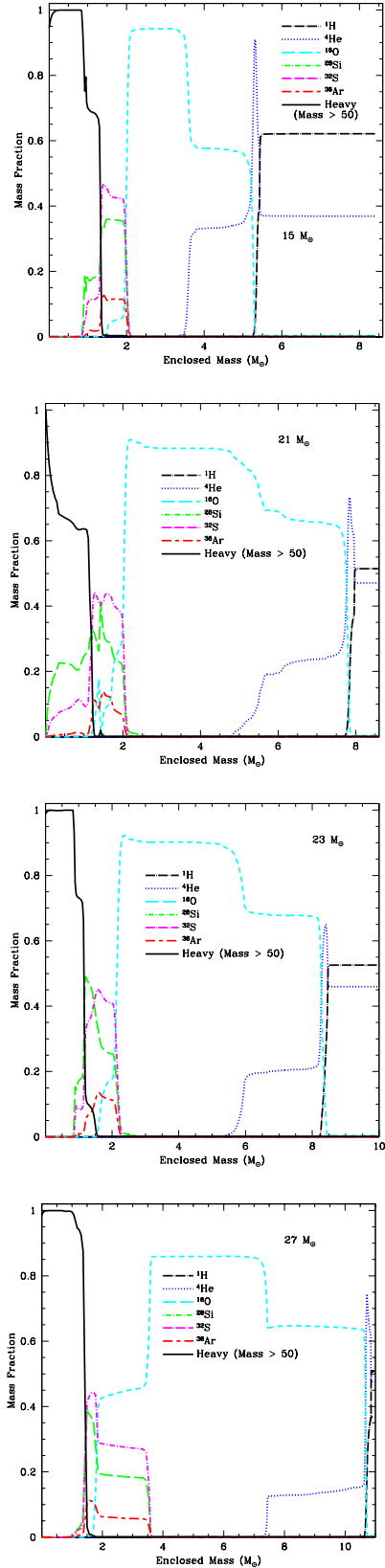


FIG. 1.— Hydrogen, helium, oxygen, silicon, sulfur, argon and heavy (atomic mass above 50) abundances for 15, 21, 23, and 27  $M_{\odot}$  stars with enhanced mixing. Above 20  $M_{\odot}$ , the convection in the helium layer burns much of the helium. This burning becomes more complete with more massive progenitors.

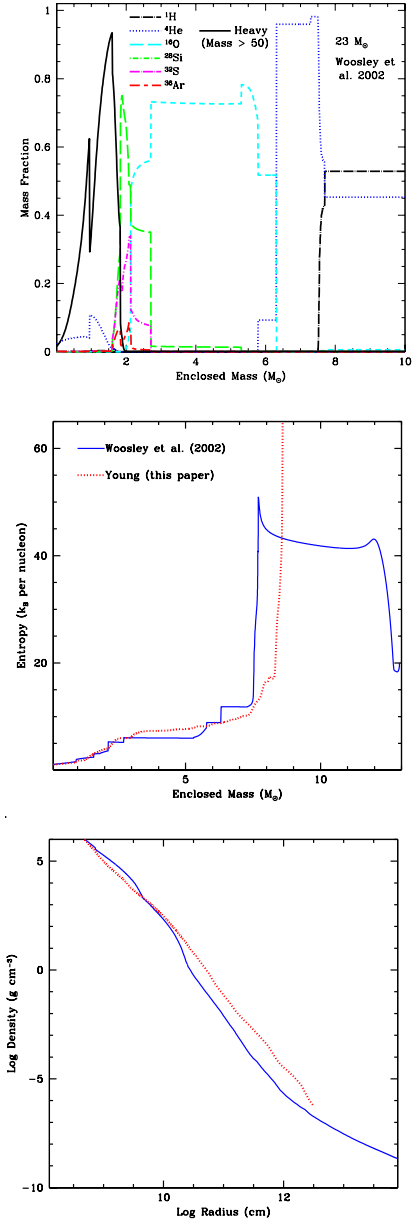


FIG. 2.— Top Panel: Same abundances (H,He,O,Si,S,Ar,heavies) as Fig. 1 for a 23  $M_{\odot}$  progenitor from Woosley et al. (2002). Note the clear helium shell. Mixing also produces very different stellar structures. The Middle panel shows the entropy profile. In the “helium-shell” region, the entropy is lower in our improved convection models when compared to the 23  $M_{\odot}$  model using mixing length theory. The corresponding density profile (bottom panel) is nearly an order of magnitude higher in our improved convection model over mixing length theory.

around 400 Å, but in the Young model this is combined with oxygen absorption in the same region. At 1e4s, the oxygen absorption around 2600 Å appears only in the Young model while a helium absorption feature at 2000 Å occurs in both.

#### 4. CONCLUSION

Our new mixing algorithm produces a very different picture of the structure and composition of Ib/c SN progenitors. In addition to changing the structure of the star, this algorithm produces a “helium shell” which is increasingly dominated by oxygen as the mass of the star

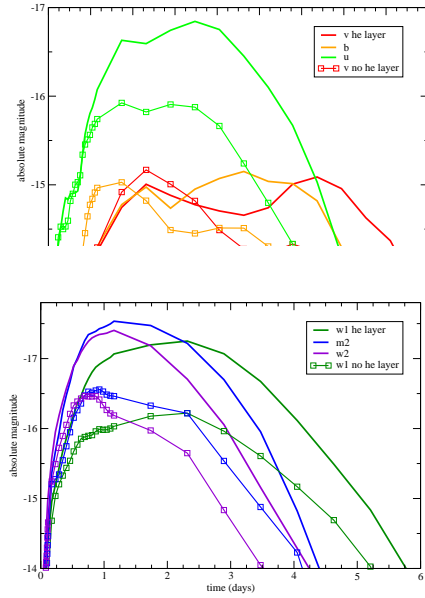


FIG. 3.— UV/optical lightcurves for both stellar models, for six Swift filters.

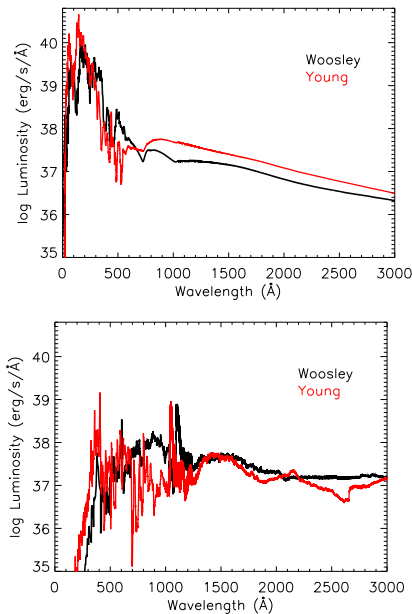


FIG. 4.— Spectra from the Young and Woosley models at 1e3 s (top) and 1e4 s (bottom).

increases. We expect stars with masses above  $\sim 20 M_{\odot}$  which lose their hydrogen envelopes (either through common envelope evolution or winds) to produce Ic supernovae. The standard long-duration GRB engine assumes that the progenitor star must collapse to a black hole, arguing that long-duration GRBs are only produced by stars more massive than  $\sim 20 M_{\odot}$  (Fryer et al. 1999). In this manner our new progenitors, employing a more physically-based algorithm for stellar convection, provide a natural explanation for why GRB-associated supernovae are all type Ic.

Depending upon the initial mass function for stars, the minimum mass for core-collapse and the minimum mass for black hole formation, stars above  $\sim 20 M_{\odot}$  can produce 10-40% of all supernovae. If Ib/c supernovae were only produced in systems with large winds, we'd expect these supernovae to be limited to stars above  $\sim 20 M_{\odot}$ , arguing that all Ib/c supernovae would actually be Ic supernovae. Many Ib/c supernovae are produced through common envelope mass ejection, producing the combination of Ib and Ic supernovae. Nevertheless, with our new progenitor stars, it is not surprising that Ic supernovae dominate the Ib/c rate.

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